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Art. X.—*A New Method of Determining the Mechanical Equivalent of Heat.*

BY

Professor T. H. LABY, M.A.

AND

J. K. ROBERTS, B.Sc.

(Natural Philosophy Department, University of Melbourne).

(With Plates X. and XI. and 1 Text Figure.)

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Introduction.

It appeared to the writers that an additional direct determination of the mechanical equivalent of heat would be of value, and might, in view of the progress of precise measurement, attain higher accuracy than that previously realised, and, incidentally, information might be obtained as to the accuracy of the electrical units.

After a long series of preliminary experiments, a method, in which a copper cylinder is heated by a rotating magnetic field, has been devised, possessing the characteristics—(1) of accurately stationary temperatures, and (2) that a small fraction of the heat developed is lost. This method is being carried out so as to attain, if possible, an accuracy of 1 in 10,000 in J, the mechanical equivalent of heat.

Previous Determinations.

There have been five determinations[1] of the mechanical equivalent of heat, to which it is necessary to refer—namely, those made by Joule, Rowland, Misculescu, Reynolds and Moorby and Rispail. Of these experiments only those of Rowland and of Reynolds and Moorby appear to possess high accuracy, and they are not immediately comparable, as the values of J, which they give, are in terms of different heat units. Several determinations have been made of what may be called the electrical equivalent of heat. If the mechanical equivalent, J, were known to an accuracy of 1 in 10,000 (which should not be beyond attainment), the degree of its

1. Joule, Phil. Trans., Vol. CXL. p. 61 (1850); Rowland. Proc. Amer. Acad., Vol. XV., p. 75 (1879); Miculescu. Journ. de Phys., Vol. I., p. 104 (1892); Reynolds and Moorby, Phil. Tran. Vol. CXC., p. 301 (1897); Rispail, Ann. Chim. Phys., Vol. XX., p. 417, (1910).

agreement with the electrical equivalent would be an indication of the accuracy with which the practical electrical units realise their intended values.

Principle of the Experiment.

The method to be described, we believe, has not, been previously applied. Baille and Féry[2] proposed to generate heat, not by stirring water, but by placing a copper cylinder in a rotating magnetic field produced by polyphase currents. Their proposal is open to the objection that the lines of magnetic force would probably have a component of motion in the direction of the axis of the copper cylinder. Heat would then be generated to which there was no corresponding couple. We have obtained a rotating magnetic field with a known and fixed axis, A, by the rotation of an electro-magnet. A copper cylinder is mounted (see Figs. 1 and 2) so as to be capable of rotation about a vertical axis, B, and is

2. Comptes Rendus., Vol. CXXVI., p. 1494 (1898).

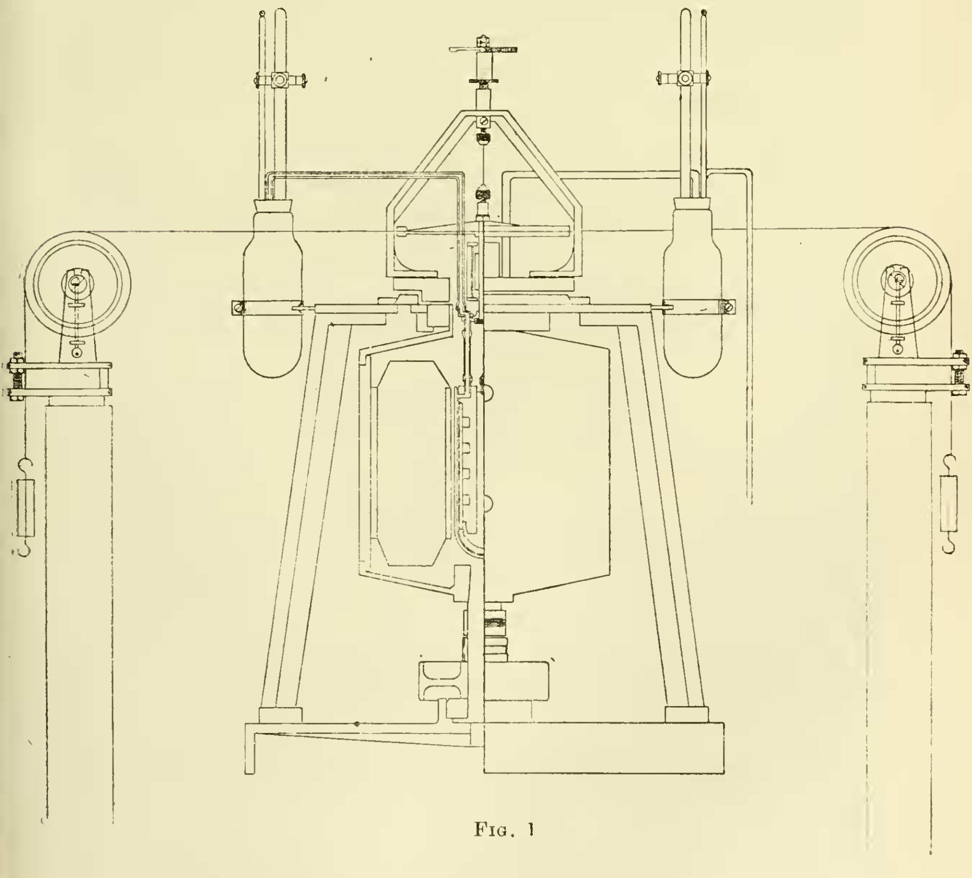

FIG. 1

placed in the rotating field. The axes A and B are brought into coincidence. The determination of J then becomes a question of finding the work done on the copper cylinder, and the heat developed in it. The work is found as in Rowland's experiment. The copper cylinder is attached to a vertical axle and wheel (diameter, D cm); and the whole is suspended by a torsion wire. Two wires pass round the circumference of the wheel over pulleys to two masses of m gm. The couple mgD dyne.cm. produced by these weights balances the couple arising from the rotating magnetic field. The torsion wire gives stability to the system.

The heat developed is measured by a continuous flow method. Water flows past a platinum thermometer, then it circulates round the copper cylinder and out past a second platinum thermometer. The heat developed is $M(\theta_2-\theta_1)$ calorie, where M gm. is the quantity of water flowing in an experiment, and $(\theta_2-\theta_1)$ degree is the rise of temperature. To eliminate the heat losses, L calorie, from the expression for J, two experiments are made—a heavy and a light one—in which the inlet and outlet temperatures θ_1 and θ_2 are the same. The heat developed in the former is about ten times that in the latter. We then have for the heavy experiment

$$\pi D n m_1 g = J(\theta_2-\theta_1)M_1 + L$$

and for the light

$$\pi D n m_2 g = J(\theta_2-\theta_1)M_2 + L$$

and therefore

$$J = \pi D n g(m_1-m_2)/\{(M_1-M_2)(\theta_2-\theta_1)\}$$

where n is the number of revolutions of the field magnets for the period of an experiment, which is the same for the light and heavy experiments.

The heat developed in the light experiment is made less than in the heavy experiment by reducing the strength of the magnetic field.

In the above relation it is assumed that the loss of heat, L, is constant for a given value of the inlet and outlet water temperatures. The text-book accounts of Callendar and Barnes' experiments[3] lay inadequate stress on the conditions which those observers showed must be fulfilled for this assumption to be justified. In our preliminary experiments the loss of heat, L, bore little relation to the inlet and outlet water temperatures, θ_1 and θ_2. With θ_1 and θ_2 fixed, L would vary widely with the rate of flow of the water through the copper, which was then in the form of a hollow copper ring. After the factors which determined the heat losses in this form of the apparatus had been determined by a number of experi-

3. Callendar, Phil. Trans., Vol. CXCIX., 1902, pp. 112, 114, 115, 122. Barnes, Phil. Trans., Vol. CXCIX., 1902, pp. 224-228.

ments, the apparatus now being described was designed so that the inlet and outlet water temperatures would determine the surface temperatures of the calorimeter, and so for a given temperature of the surroundings of the calorimeter, determine the loss of heat, L, independently of the rate of development of heat in the calorimeter.

The equation we have given assumes that three axes are parallel, namely, the axis of rotation of the magnetic field, the axis about which the copper cylinder is free to rotate, and the axis of the couple produced by the two masses m. This condition is fulfilled to the required accuracy in the apparatus as we are using it.

In another paper,[4] the theory of the electrical device, which we have used in these experiments, is given. It is there shown that the couple ψ dyne.cm. acting on the stator is given by the expression

$$\psi = \pi\rho N\phi^2 / \left\{ \rho^2 + 4\pi^2\lambda^2 N^2 \right\}$$

where N revolution per sec. is the speed of the rotor, ϕ maxwell is the flux crossing the copper cylinder, ρ is proportional to the resistance from end to end of the cylinder, and λ cm. is a certain inductance.

Design and Operation of the Apparatus.

It will be convenient to call the rotating field magnets, the rotor, and the copper cylinder and the iron cylinder which it encloses, the stator.

The rotor (see Figs. 1, 2, 3 and 4) is mounted on ball bearings, with its axis vertical. The field magnet windings are connected through slip rings to a lead storage battery. The rotor is belt-driven by a shunt motor, and the speed of the former is determined by means of a worm gear, which, at the completion of every 100 revolutions (that is, about every four seconds), moves a pen writing on a chronograph; the pen also indicates seconds, as given by a standard clock. In this way, the rate of rotation and number of revolutions is recorded.

The rotor is pierced with eight sighting holes (see Figs. 3 and 4) for adjusting the axis of the stator parallel to that of the rotor. These holes, if fully open, thoroughly ventilate and cool the field magnets.

The lower bearing of the rotor is rigidly held by an iron bed plate bolted to a brick foundation. In order to prevent vibration in the plate, which carries the upper bearing of the rotor and the

4. J. K. Roberts. The Design of a Motor with Large Air Gap and Rotating Field Magnets. Proc. Roy. Soc. Vict., XXXII., 1920, p. 156.

bearing of the stator, the rotor was balanced. Suitably illuminated points situated on the plate in question were observed with a microscope, carried by a support free from vibration, and the rotor was balanced until the amplitude (i.e., diameter of circumscribing circle) of the vibration of the plate was reduced to .001 cm.

The field magnets have two poles, and there are two windings on each pole. These windings can be connected in series so that the turns reinforce one another, and the maximum flux for a given current produced. They are so connected for the heavy experiment. The windings can also be connected in series so as to oppose one another in their magnetising effect. They are so connected for the light experiment. In this way the flux can be reduced to one-tenth without changing the current in the windings and, therefore, without changing the temperature of the rotor in the light and heavy experiments.

The Stator and Calorimeter.—The construction of the stator is shown in Figs. 5, 6 and 7. Fig. 5 shows copper and iron cylinders. The iron cylinder increases the magnetic flux, and supports the copper cylinder. The channels on the external surface of the iron, and the axial hole, carry the water in its circulation through the apparatus. The iron cylinder is attached to a glass tube (see Fig. 6) filled with eider down. in order to reduce loss of heat by conduction. The glass tube in turn is attached to a steel shaft which passes through a ball-bearing, and, at its upper end, is suspended by a steel torsion wire. The wire supports the whole weight of the shaft and calorimeter.

A thin sheet cylinder encloses the copper cylinder, and a Dewar flask encloses the steel, copper, and iron cylinders, which to prevent corrosion are all silver plated.

The water enters the calorimeter (see Figs. 5, 6 and 7) through a rubber tube, flows downwards between the inside wall of the Dewar flask and the thin steel cylinder, turns upwards and flows between the steel and the copper, then down between the copper and iron, and finally out of the calorimeter through the axial hole in the iron armature. The object of this somewhat elaborate circulation is—(1) to bring the water into thorough contact with the copper and iron in which the heat is generated, (2) to break up stream lines, and so ensure that the inlet and outlet water temperatures determine the heat losses of the calorimeter.

The ball bearing which maintains the shaft vertical was very carefully made, and is used without oil lubrication, which was found to increase the friction. The angular amplitude of the stator when set in torsional oscillation decreases by 10 per cent. per vibration, from which it can be shown that the friction is very small. A mirror is attached to the shaft of the stator, and its movement observed by lamp and scale. With the apparatus arranged for a determination of the mechanical equivalent, the stator oscillations are not critically damped; frictional resistance arising from the viscosity of water is added, till the damping is critical.

Couple.—Two thin wires (see Fig. 1) pass from the circumference of the wheel over two other wheels (see Fig. 2), and then to the weights. With the axis of the stator vertical (which it is to within 12′ of angle) these wires should be parallel and horizontal, conditions which are readily fulfilled.

The design, construction and testing of the wheels shown in Fig. 8 has required a great deal of attention. Ball, roller, and cone bearings were tested, and found to possess far too much friction to be suitable for these wheels, and so a knife edge was used. While this bearing is quite free from friction, and practical in use, it is necessary to locate the position of the knife edge relative to the centre of the wheel, a test which is not so easily made as might be expected.

Measurements.

The relation

$$J = \pi D n g (m_1 - m_2) / \{ (M_1 - M_2)(\theta_2 - \theta_1) \}$$

indicates what degree of accuracy is necessary in the various quantities in the right hand member, if J is to be correct to 1 in 10,000.

D, the diameter of the wheel, is 20 cm., and can be measured to the necessary accuracy. The revolutions, n, are counted. The acceleration of gravity, g, is accurately known for Melbourne. The masses, m_1 and m_2 gm., are readily found to the required precision.

With $\theta_2 - \theta_1 = 10°C$. it is necessary to determine this difference to 1/1000°C, which is about the limit of accuracy obtainable with a platinum, or, in fact, any thermometer. The water flows past the platinum thermometers contained in Dewar flasks, as shown in Fig. 2.

The water, after passing through the calorimeter is collected in a copper can. A two-way tap turns it into this can at the beginning of the experiment, and at the same time starts the chronograph record; at the end of the experiment turning the tap causes the water to flow to a different vessel, and also stops the chronograph record. The water collected is weighed.

Distilled water contained in two thermally insulated tanks, so arranged as to give a constant head of about 240 cm. (8 feet) is used in the experiments.

The precision of the experiments will be limited (1) by the steadiness in the rate of generation of heat, and (2) by constancy of the loss of the heat, L, in the heavy and light experiments. The first of these has been satisfactory in the preliminary experiments, and if necessary, could be improved. The principal loss of heat, no doubt, occurs through the walls of the vacuum jacket of the calorimeter, and is proportional to the excess of the temperature of the inner wall (that is, the temperature of the inlet water θ_1) above the outer wall (that is, the air temperature θ_a). This difference $(\theta_1 - \theta_a)$ degree can be determined, it is expected, with sufficient accuracy to attain the desired precision.

Only preliminary determinations of J have so far been made, further experiments are now in progress.

We have to thank Mr. R. Berryman for the care he has taken and the success he has achieved in constructing the apparatus shown in the figures.

DESCRIPTION OF PLATES.

Plate X.

Fig. 2.—General view of apparatus.

,, 3.—Rotor with top removed, showing pole pieces and windings.

,, 4.—Rotor mounted.

Plate XI.

,, 5.—The two parts of the stator, on the left the iron cylinder in the channels for water, on the right the copper cylinder fitting over it.

Fig. 6.—Stator attached to torsion wheel with flask removed.

,, 7.—Stator with flask attached, showing plate with levelling screws resting on the top plate of Fig. 5.

,, 8.—Knife edge bearings.

[Note added 10th March, 1920 :—Improvement in the brush contacts on the rotor has led to greater steadiness in the rotor field magnet current and therefore in the couple; this has made the water damping device mentioned in the text unnecessary.

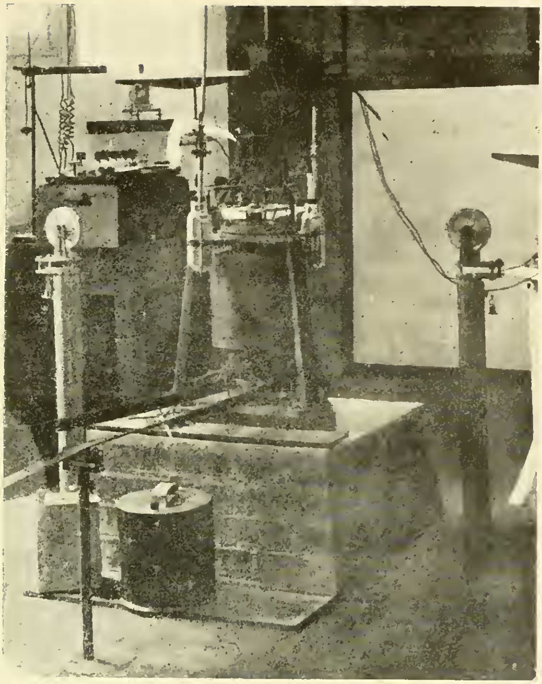

Fig. 2. General View of Apparatus.

Fig. 3. Rotor with top removed, showing pole pieces and windings.

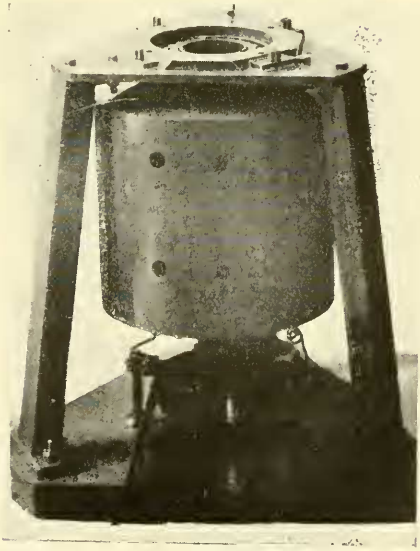

Fig. 4. Rotor mounted.